AFIT/GEO/MA/81D-1

ANALYSIS AND PREPARATION OF A
DIGITAL TERRAIN DATA BASE FOR
FLIGHT SIMULATOR USE

THESIS

AFIT/GEO/MA/81D-1   Harry D. Ross
2nd Lt   USAF

JUN 1 5 1982

AFIT/GEO/MA/81D-1

ANALYSIS AND PREPARATION OF A

DIGITAL TERRAIN DATA BASE FOR

FLIGHT SIMULATOR USE

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

in Partial Fulfillment of the

Requirements for the Degree of

Masters of Science

by

Harry D. Ross
2nd Lt   USAF

Graduate Electrical Engineering

November 1981

Table of Contents

i

List of Figures

List of Tables

ABSTRACT

The Air Force needs low-level, high speed flight simulators capable of producing correlated visual, radar, and infra-red display scenes. These scenes can be produced by computer generated imagery if a suitable data base is available.

The purpose of this thesis is to develop a digital terrain data base suitable for use in a high speed, low-level flight simulator. A 164,000 square nautical mile data base was constructed from data supplied by the Defense Mapping Agency. This paper discussed the construction and organization of the data base, as well as the data retrieval algorithms. It was demonstrated that the data could be accessed fast enough to simulate Mach 1 flight.

1. INTRODUCTION

1.1 Background

Over the past several years the Air Force has been placing increased emphasis on conducting training in flight simulators rather than in the aircraft. This saves money by helping to conserve energy and reducing wear on aircraft. A typical flight hour can cost as much as $3000 including crew, maintenance, and hardware depreciation costs. Simulators also allow aircrews to perform maneuvers that would be dangerous to practice in the aircraft. Simulators are also used to test new equipment and algorithms for on board computer systems.

Current Air Force needs require simulators capable of producing an out-the-window display over large areas of terrain. A typical mission may require a 100 mile ingress to a target area, all flown at low level. Terrain boards are often used to produce a visually realistic display, but are limited in size. The largest terrain board the Air Force has covers an 18 by 50 mile area. Terrain belts can simulate flight over longer distances, but the terrain features are repetitive.

While flying at low levels, the ground is the pilot's

1

biggest threat, and requires his constant attention. This leaves little time for looking at other sensors, such as radar and infra-red imaging systems. The Avionics Laboratory at Wright-Patterson AFB is involved in the development of a system to fuse information from various subsystems. This system will coordinate these sensor displays with the pilot's out the window view. This will enable him to find a target more easily, once it shows up on a sensor display. To test these systems will require a simulator capable of producing coordinated visual, radar, and infra-red displays.

There is also a need to test new Terrain Following and Terrain Avoidance (TF/TA) systems and algorithms over various types of real world terrain. Terrain boards and belts are visual models and most do not accurately depict the Earth's surface. Also, they are not easily changed to simulate flight over different types of terrain.

1.2 Problem

A simulator that can provide the opportunity to experiment with terrain following algorithms, correlated sensor images, and variable terrain must be found so that future avionic systems can be evaluated with fewer flight test hours. It is much cheaper to make changes in design in a laboratory than on a flight aircraft. In addition total system performance can be compared relative to various terrain threats, fire control or other functions.

A simulator using computer generated imagery would be capable of producing both an out-the-window visual display and a radar display. Such a simulator requires a data base which covers very large areas, and which accurately describes real world terrain features. Such a data base is available from the Defense Mapping Agency (DMA). Their data base is comprised of two types of data, one describing the terrain features on the Earth's surface, and the other describing primarily man-made features. These data are readily available for areas covering most of the Earth, but they cannot be used directly.

The purpose of this effort is to develop a terrain data base for flight simulators, using DMA data as a source. The data base is to be used to produce visual displays capable of simulating low level flight at speeds up to Mach 1, over a 500 by 500 mile area.

1.3 Approach

The terrain data supplied by DMA is organized into records that contain a lineal arrangement of elevation values. A typical record has an area of coverage equal to 69 miles by 300 feet. This is unsuitable for direct use since a display will only cover a few square miles at a time. A new data base is to be created which will be organized into smaller records, each covering a rectangular area. These

3

records will much more closely match the requirements of a simulator.

The DMA data are organized along latitude and longitude lines. The horizontal distance between elevation values, or elevation posts, varies continuosly with a change in latitude. In order to produce a realistic view of the terrain this changing spacing must be used when generating a display. To prevent having to calculate the spacing every time the display changes, the horizontal spacing is made constant throughout the new data base.

The data base developed in this thesis is a first attempt, prototype to be used to test the requirements of a high speed, low level simulator. This effort is limited to the construction of a prototype data base and the algorithms to retrieve the data. Actual tests will use an "Evans and Sutherland Picture System" calligraphic display system. However, these test results are not part of this work.

The methods developed were implemented on a "DEC-10" computer. All code was written in Pascal. This language was used because of its flexible data types. By defining records, parts of a word could be easily addressed and used to hold 16-bit elevation values on a 36-bit machine. the "DECsystem-10" version of Pascal has many additional features which make it easier to read the non-standard tapes supplied by DMA.

4

1.4 Assumptions

The algorithms developed assume that the radius of the Earth is constant over the area covered by the prototype data base. Over the entire Earth's surface the radius varies from 6,378,130 meters to 6,356,751 meters [Ref 10]. Since the data base is regional and is not to extend more than several hundred miles in any one direction, the constant radius assumption should be valid for most areas. The term nautical mile (nmi) is used to describe the distance equal to one minute of arc on the Earth's surface. For the above range of the radius this gives the range 1855.32 to 1842.10 meters for a nautical mile. During construction of the data base the value 1853.25 meters is used for a nautical mile. The actual radius used was derived from the radius of a sphere with the same surface area as the Earth. If a more accurate value is known, it can be put in the algorithms used to display the data without any change to the data base.

It is assumed that the DMA data is accurate and complete. The validity of this assumption depends upon the area covered by the data base, and the age of the source data. DMA is continuously improving their methods of production, but some of the data they release does not meet their product specifications. Some of the older data is known to contain many problems, such as random spikes and discontinuities in the surface.

5

2. THE DIGITAL LANDMASS SYSTEM

The terrain data used in this effort is part of the Digital Landmass System (DLMS). The DLMS is produced jointly by the Defense Mapping Agency Aerospace Center (DMAAC) in St. Louis, Missouri and by the Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC) in the Washington D.C. area.

The Digital Landmass System Data Base is comprised of two types of data: Digital Terrain Elevation Data (DTED) and Digital Feature Analysis Data (DFAD). DTED consists of the latitude, longitude, and elevation of terrain features on the Earth's surface at predetermined horizontal intervals. This information is extracted from charts and photographs and stored in digital form as described below. DFAD consists of feature or cultural data such as tree heights, vegetation, rivers, lakes, railroads, roads, buildings, and other natural and man-made features. The shapes, sizes, and locations of these features are placed in digital format along with a code that represents the types of materials and associated radar reflectance characteristics.

Since this effort is limited to the development of a terrain data base, only the terrain data supplied by DMA was used.

6

2.1 Production

The DTED files are derived from two sources: existing maps (cartographic) and aerial photography (photographic). When existing maps are the source, the data is obtained by digitizing contour lines and lines representing mountain ridges and streams. Since the elevations along the contour lines do not directly provide values for each grid point in the DTED file, the elevation of points not on the contour lines must be obtained via interpolation.

When producing DTED from photography, a machine automatically scans a stereo pair of aerial photographs and records an elevation value at each point on a rectangular grid. Since this grid is not the same as that in the DLMS, elevations must be derived by interpolation from the elevations at points in the scanner grid. Where the photographs contain cloud cover or smooth, flat areas such as lakes or mud flats, the scanner cannot determine the elevation. For these areas, the elevation data must be obtained by other means and patched into the DTED file.

A detailed discussion of the processes involved in DTED production is contained in a report by Frank N. Drobot et al. [Ref 2].

2.2 Organization

DTED is produced at two different levels of resolution. The bulk of the terrain data is produced at Level 1. Level 2 has the finer resolution and is produced for special applications over small areas. The surface sampling rate for a DTED file depends not only upon the resolution level but also upon the file's starting latitude or zone. Table 2-1 lists the sampling rates for the various zones used by DMA. Because the surface spacing of the longitude lines varies, the East-West sampling interval is different at every latitude, while the North-South sampling interval remains fixed. Table 2-2 lists the range of the sampling intervals in each of the zones for Level 1 DTED.

All terrain files supplied by DMA are recorded on magnetic tape in DMA Standard Terrain Format [Ref 8].

2.2.1 Files

Terrain data files are arranged into geographic areas covering one degree of latitude by one degree of longitude. The reference origin for each data file is the Southwest corner of the one degree square. To provide overlap between adjacent data files, the degree square coverage includes the integer degree value on all sides of the area. Multiple data files on a tape are arranged primarily by ascending latitude bands, (90 S to 90 N) and secondarily by ascending longitude (180 W to 180 E).

Zone	Latitude	Level 1 lat. long.	Level 2 lat. long.
I	0°-50° N-S	3 x 3 seconds	1 x 1 second
II	50°-70° N-S	3 x 6 seconds	1 x 2 seconds
III	70°-75° N-S	3 x 9 seconds	1 x 3 seconds
IV	75°-80° N-S	3 x 12 seconds	1 x 4 seconds
V	80°-90° N-S	3 x 18 seconds	1 x 6 seconds

NOTE: All values in seconds are in terms of arc measure.

Table 2-1: Latitude and Longitude Interval
Between Elevation Posts for
Level 1 and Level 2 DTED

DTED Level 1		
Zone	Spacing (meters)	
	Latitude	Longitude
I	92.7	92.7 to 59.6
II	92.7	119.1 to 63.4
III	92.7	95.1 to 71.9
IV	92.7	95.9 to 64.4
V	92.7	96.5 to 0

Table 2-2: Distance Between Elevation Posts
for Level 1 DTED

9

2.2.2 Records

All the elevations within a data record have the same longitude value. The first data value is the southern-most known elevation and the last is the northern-most. Unknown values internal to the record are indicated by null values. No two data records within a file have the same longitude value. The records within a file are arranged in order by ascending longitude.

2.2.3 Fields

All elevation values are represented by 16 bit, signed magnitude binary integers, right justified. The sign is in the high order position. Negative values are not complemented and null values are represented by all one bits. The permissible elevation range is -32766 to +32767 meters.

Figure 2-1 shows the record ordering for four one degree square files with 12 minute longitudinal spacing. Detailed information on the tape format, including the label format and record descriptor fields can be found in the DMA Product Specifications [Ref 8].

2.3 Using DTED Files

To provide random access to the DTED files, they were reformatted and transfered to a disk. The same basic organization was retained. That is, each file still covers a one degree square and all the posts in a record have the same

10
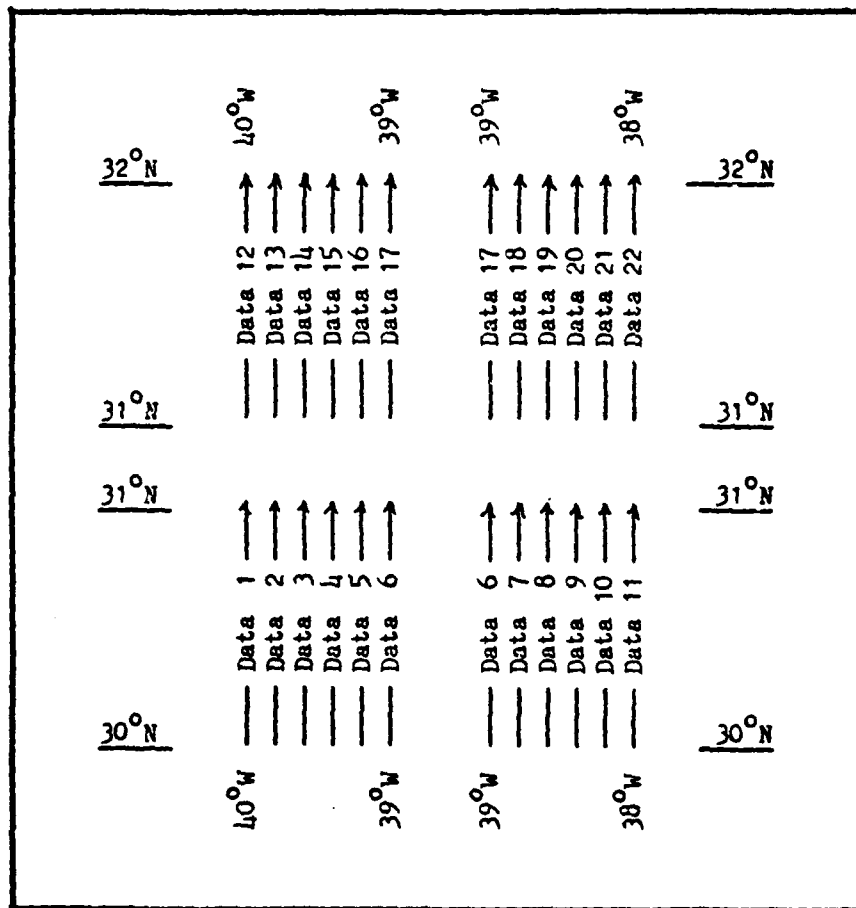
Figure 2-1: DMA Standard Terrain Example
Four One Degree Squares
12' Longitude Spacing

longitude value.   In order to randomly access a file all the
records must be a fixed length.   Therefore, null fields were
added to compensate for unknown elevation values along a
longitude line.   Since the Dec-10 has a 36 bit word,
elevations were packed two to a word in 16-bit signed
magnitude notation.

11

The first time a file was read from tape it was assigned a file name, "DMA.xxx", where xxx is a sequential count of the different files transferred from tape (e.g. 001, 002, 003, ...). Only elevation data was put into the file, all pertinent information describing the file location and content was placed in a second file, "DMA.PTR". This file is a look-up table that contains

the latitude and longitude of the South-West corner,

the file id number,

the grid interval,

the total number of known elevation posts,

and the type of errors that occured, if any,
while reading the file.

3. PROTOTYPE DATA BASE

3.1 Organization

All elevation posts in the prototype data base lie on an evenly spaced grid. That is, the post separation in the North-South and the East-West directions are equal. Unlike the DLMS, in which the grid spacing varies continuously with latitude, the grid spacing is constant throughout the prototype data base.

The elevation posts can be considered organized into East-West rows and North-South columns which extend the width and height of the data base. All the posts in a row have the same latitude value. The center column of the data base coincides with a longitude line. This is the only column in the data base in which all the posts have the same longitude value. All the posts in a column share a common distance from the center column. This distance is measured along the rows. Since this distance is measured along lines of constant latitude, it is not the shortest distance or the great circle distance between the posts. The grid spacing used in this prototype data base is 1/20th of a nautical mile or 92.6625 meters. This spacing corresponds to the 3 second latitudinal spacing in the DLMS Level 1 DTED used as a source.

The whole data base is contained in a single file, but since only relatively small areas will be used at a given time, the data base is subdivided into records. Each record contains a 20 by 20 array of elevation posts and covers one square nautical mile. The southern edge of a record lies on a latitude line with an integer minutes value (e.g. 43° 14' 00"). The record extends to the North to one post below the the next integer minute latitude line (e.g. to 43° 14' 57"). The western-most column of the record is an integer number of nautical miles from the center column of the data base. The record extends East to one post short of the next integer distance from center. For example, the edges of a record West of center would be:

```
South - 44° 37' 00" N
West  - 108 nmi West of center
North - 44° 37' 57" N
East  _ 107.05 nmi West of center
```

Records are numbered and placed in the file in sequential order. The first record, record number 0, covers the South-West corner of the data base. The remaining records in the data base are numbered in a West to East, then South to North sequence. Figure 3-1 is an example of the record order of small data base. There is no overlap of adjacent records.

14

8	9	10	11
4	5	6	7
0	1	2	3

N ↑ ↳ E
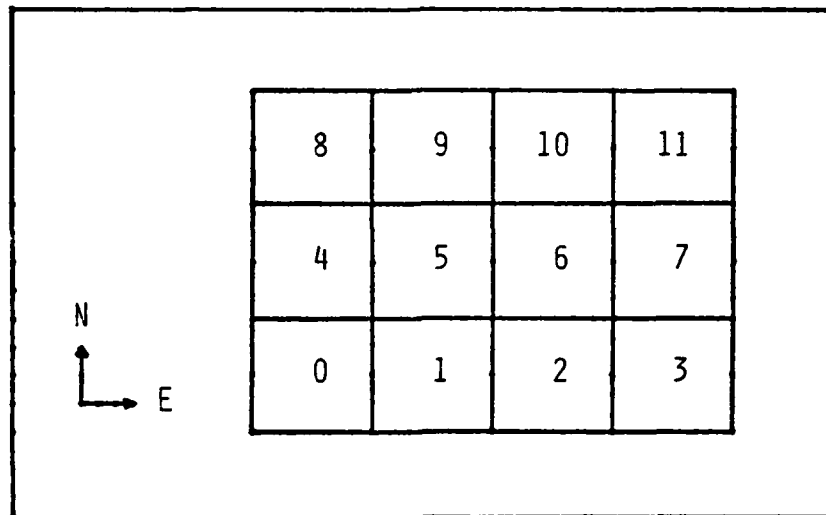
Figure 3-1: Record Order for a 3 nmi by 4 nmi Data Base

3.2 Construction

The first step in constructing a data base is to define its area of coverage. A North-South center line is chosen which will be the center longitude or center column used as a reference when measuring distances in the data base. Next a southern edge is chosen which will be the bottom or base latitude of the data base. Both the center longitude and base latitude are chosen to correspond to values that are in the source DTED. To complete the definition two distances are needed, the height and half width of the data base. The height is the distance the data base extends North from the base latitude. The half width is the distance the data base

15

extends to the East and West from the center column. Both distances are specified to be an integer number of nautical miles. Figure 3-2 is an example of a small data base overlayed on the DTED grid. The grid spacing in the new data base equals the latitude spacing in the source. For Level 1 DTED this interval is 92.6625 meters. The elevation post spacing along a row in the source DTED (Level 1, Zone I) is equal to 92.6625 times the cosine of the row's latitude.

Figure 3-2: Overlay of New Data Base Grid on DTED Source Grid

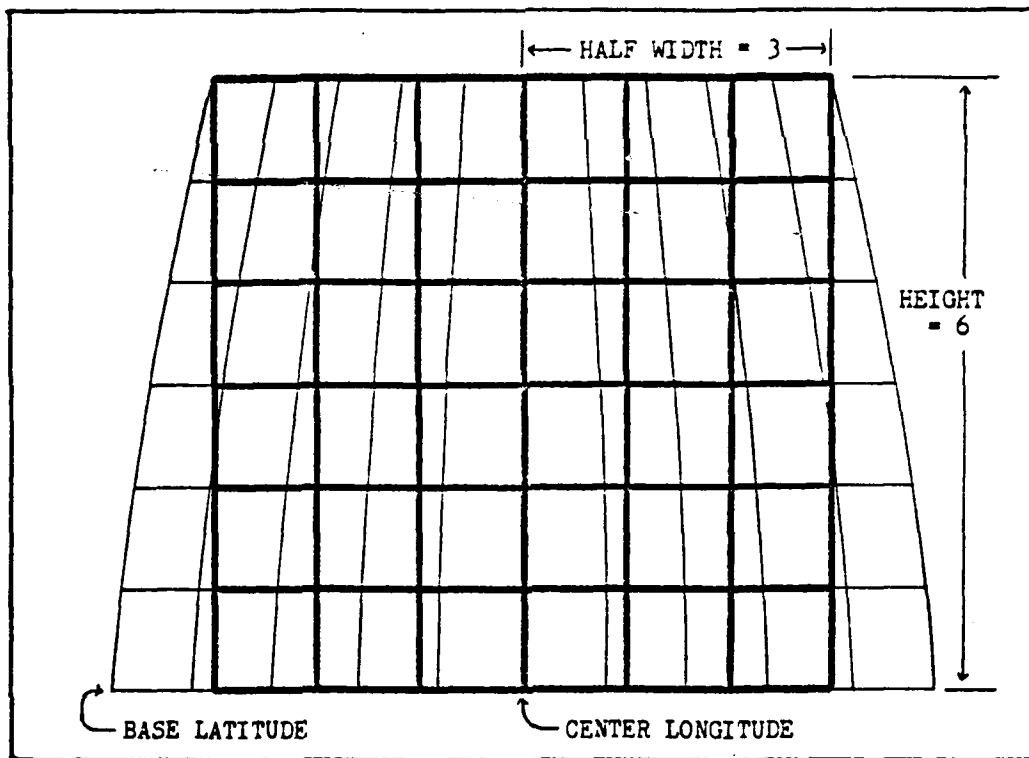Records are formed one at a time and in order. An area of DTED a little larger than the desired record is read from disk. This area extends several posts beyond the East and West edges of the record. Since all the posts in a row of the record also lie on the same row (latitude) in the DTED, a one-dimensional interpolation is all that is needed to find the new elevation. A third order polynomial interpolating function is found that passes through two points on either side of the desired location [Ref 6]. The coefficients of the polynomial are found using Aitken's method of iterated interpolation [Ref 5:173-176]. The interpolating function is then shifted East, to pass through four posts surrounding the next post's location. The function is "walked down" the row until all 20 posts are found The process is repeated for the remaining rows in the record, and then for the remaining records in the data base.

3.3 Compaction

The prototype data base covers an area 420 by 390 nautical miles or 163,800 square nautical miles. Thus it contains 163,800 records, each containing 400 elevation posts. Therefore 65,520,000 16-bits words are needed to store the data base. By placing two elevation posts per 36-bit word, the entire data base could fit on one of the DEC-10's 200 MByte disk packs. However, since a whole disk pack was not available and because it was not desired to use

17

that much storage space the data base needed to be compacted further.

There are several methods available to compact the data. Many of them at the expense of accuracy and/or resolution. The more popular methods represent the data as a set of localized functions, that must be evaluated over their area of coverage to obtain the elevation posts. Since rapid access to the elevation data was desired, it was believed that these methods would be computationaly burdensome to implement on a general purpose digital computer. While able to obtain a high degree of compaction, 45 to 1, there is some question as to the ability of these functions to represent the original data [Ref 4].

Since a great deal of compacting was not needed, a simple method of compaction was developed. Each record was divided into 20 rows of 20 posts each. The first post in each row was stored in its full sixteen bits. The second and subsequent posts are stored as nine bit offsets from the previous post. To simplify compaction and unpacking, excess 256 notation was used to represent the offsets.

Each line requires 16 + (9 * 19) or 187 bits of storage and each record requires 3740 bits. This results in a 27% reduction over the 5120 bits need per record to hold all elevation posts in their full sixteen bits. Over the area

18

covered by the prototype data base, an average of 9152 bits per square nautical mile would be needed to store all the elevation posts in the original DTED. This method of reorganization, regridding and compaction results in an overall 59% reduction in required storage space.

Additional fields were added to each record to aid in debugging. The records were also padded with blank fields to make the record size compatible with the disk block size on the DEC-10. The blanks are not necessary, but were added to reduce the time required to transfer one record from disk. Figure 3-3 is an example of the Pascal type and variable declaration used for the data base.

3.4 Access

Normally references to geographic locations are given in latitude and longitude, but since the data base is not organized along those coordinates, the latitude and longitude must be converted to the data base reference system. Each elevation post in the data base can be addressed by an integer pair, (x,y), where x is the column number and y is the row number of the post. Let the elevation of the post at (x,y) be represented by the function New_Post(x,y). Then the elevations at the four corners of the data base could the be found by

```
(*******************************************************)

TYPE

   nine_bits = 0..777b;

   line = RECORD
             start : INTEGER
                         (* 1st post, stored in 1 word *);
             next : PACKED ARRAY[0..19] OF nine_bits
                         (* 5 words *);
          END  (* Record requires 6 36-bit words *);

   data_base_record =
          RECORD
             record_number : INTEGER;
             record_base_latitude : INTEGER
                         (* in seconds from the equator *);
             distance_from_center : REAL (* nautical miles
                         from the center of the data base *);
             elevation_posts : ARRAY[0..19] OF line;
             blank : ARRAY[1..5] OF INTEGER;
          END  (* Record requires 128 words *)

VAR

   data_base : FILE OF data_base_record;

(*******************************************************)
```

Figure 3-3: Data Base Declaration Statements

```
        SW  -  Post(0,0)
        SE  -  Post(C_max,0)
        NW  -  Post(0,R_max)
        NE  -  Post(C_max,R_max)
```

Where

```
        C_max = (the number of rows) - 1
        R_max = (the number of columns) - 1
```

20

When converting latitude and longitude to the data base coordinate system, the southern-most row, or base latitude, of the data base is used as a North-South reference datum. The center column, or center longitude, is used as the East-West reference datum. The datums "base_lat" and "center_long" are constant values that are fixed when the data base is constructed. Other fixed values that are needed for reference are:

"width_of_db" - the total East-West width of the data base in nautical miles

"lat_interval" - the change in latitude between adjacent rows, 3 seconds in the prototype data base

"grid_spacing" - the distance between data points in nautical miles

For a given latitude and longitude, "lat" and "long", the data base coordinates for the the location can be found by the operations

$$dist := (long - center\_long) * (60 \text{ nmi per degree}) * cosine(lat)$$

$$x := (lat - base\_lat) / lat\_interval$$

$$y := (dist + (1/2 * width\_of\_db)) / grid\_spacing.$$

Where

"dist" = the distance from the requested post to the center column of the data base, measured along a line of constant latitude.

An individual elevation value can not be read from the

21

disk even though its coordinates are known. A record is the smallest unit that can be transferred from the disk. Any record in the data base can be located on the disk from its record number by the "DEC-10 Pascal" procedure SETPOS(File). The number of the record which contains the value Post(x,y) can be found by the integer operations

```
record_number := ( (x DIV 20) +
                    ( (y DIV 20) * width_of_db) )
```

3.4.1 Unpacking

The record must then be expanded from its compacted form before the value of Post(x,y) can be found. The first elevation value in each line is stored in a separate word and can be transferred directly from the file buffer to a variable. let "sq_mile" be a variable array[0..19,0..19] of integer. Then for the first post in the first row

```
sq_mile[0,0] := data_base↑.elevation_posts[0].start
```

The remaining posts in the line can be found by

```
FOR j := 1 TO 19 DO
  sq_mile[0,j] := sq_mile[0,(j-1)] + (400b -
                      data_base↑.elevation_posts[0].next[j])
```

Only 38 integer operations are needed to unpack a line. The process is repeated for the other 19 lines in the record, for a total of 760 integer operations per record.

Once the record has been unpacked into the variable "sq_mile", the value of Post(x,y) can be found by

```
x1 := (x MOD 20)
y1 := (y MOD 20)

Post(x,y) := sq_mile[x1,y1]
```

3.4.2 Interpolation

Because the data base contains only discrete data points, the function Post(x,y) is defined only for integer values of x and y. Some applications require that the data base be defined continuosly over the entire area of coverage. Let the function New_post(x,y) equal the elevation at (x,y) for any real values of x and y in the range

$$0 <= x <= C\_max$$

$$0 <= y <= R\_max$$

The value of New_post(x,y) must be found by interpolation from the surrounding posts in the data base. Several techniques are available. The location (x,y) could be rounded to the nearest integer location, and the elevation at that point used for New_post(x,y). This would be the fastest, but also the least accurate method. The earth's surface could be modeled with a two dimensional polynomial function, fitted to 16 surrounding posts (i.e. 2 posts in each of the 4 directions). This would be the preferred

23

method [Ref 6], but requires too much computation to be used for a high speed flight simulation.

New_post(x,y) could be found by taking a weighted average of the four nearest posts in the data base. Each elevation value would be weighted by the inverse of the square of its distance from the desired location, and the sum of the weights would equal 1. Since distance is determined using Pythagoras' Theorem, use of the squared distance in interpolation eliminates the need for a square root determination, reducing computer processing time. A surface thus produced is continuous in the first derivative and therefore appears smooth [Ref 7]. This is the method used by DMAAC when regridding raw data to their final grid. Once the four surrounding elevations are known, 12 additions and subtractions, and 13 multiplications and divisions operations are required to find the desired elevation value. Although faster than the previous method, it was believed that this method would still be too slow since every value in a display scene may need to be interpolated.

The method finally chosen is a series of linear interpolations among the four posts surrounding the desired location. The value of new_post(x,y) can be found by the following sequence. See Figure 3-4.
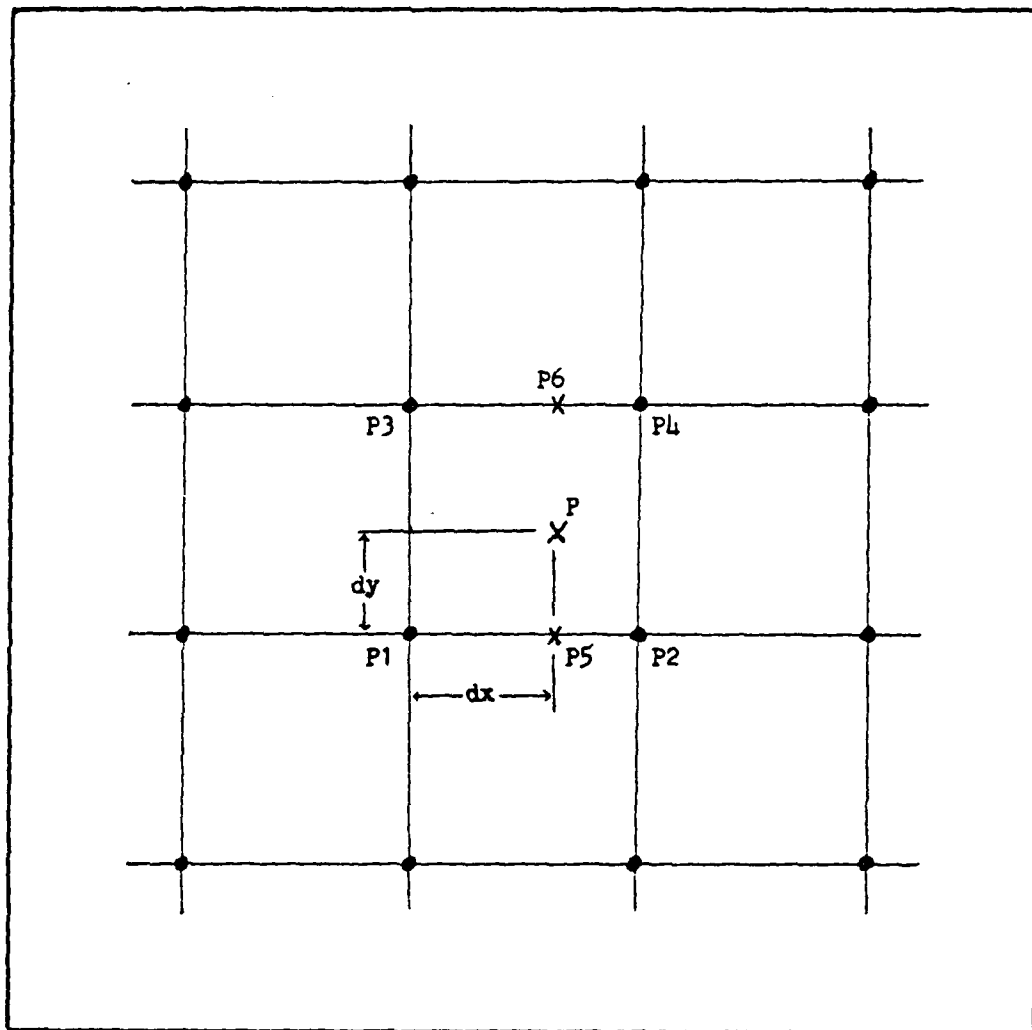
24

Figure 3-4: Linear Interpolation in a Square Grid

25

```
x0 := TRUNC(x);
y0 := TRUNC(y);

pl := Post(x0,y0);
P2 := Post((x0+1),y0);
p3 := Post(x0,(y0+1));
p4 := Post((x0+1),(y0+1));

dx := x - x0;
dy := y - y0;

(* interpolate between pl and p2 *)
p5 := pl + (dx * (p2 - pl));
(* interpolate between p3 and p4 *)
p6 := p3 + (dx * (p3 - p4));

(* interpolate between p5 and p6 *)
p  := p5 + (dy * (p6 - p5));

New_post(x,y) := p;
```

Once the *four* surrounding *posts are known,* 8 additions and subtractions, and 3 multiplications are required to find New_post(x,y).

3.5 Limitations and Errors Introduced

These methods of construction, compaction, and accessing were designed to develop a data base capable of producing a visual display of the terrain over a gaming area. The gaming area on the order of 250,000 square miles, or 500 by 500 miles. When used in this context, there are no known major problems with the data base. There are several minor discrepancies which may affect the use of these methods in other applications.

If a data base is needed over an area near the poles, other methods would need to be developed because the latitude lines can not be considered straight and parallel. These methods can be used over the region 60°S to 60°N without noticeable error.

The data base is designed to have a constant data point spacing though out the entire area of coverage. The spacing was chosen to equal the spacing in the source DTED between two adjacent posts on the same longitude line. For a spherical Earth, this spacing is the same for any two posts on the sphere, because each longitude line forms part of a great circle around the Earth. In the new grid however, the North-South lines are no longer lines of constant longitude. Therefore, the spacing between posts is no longer fixed in the North-South direction. The spacing between posts in the East-West direction is calculated during the construction of the data base and is fixed, but the North-South spacing increases as the distance from the center column of the data base increases and as the distance from the equator increases.

For a data base over a region in the Northern Hemisphere, the maximum spacing error will occur between the posts in the northern-most corners of the data base. The maximum error can be found by following steps. See Figure 3-5.
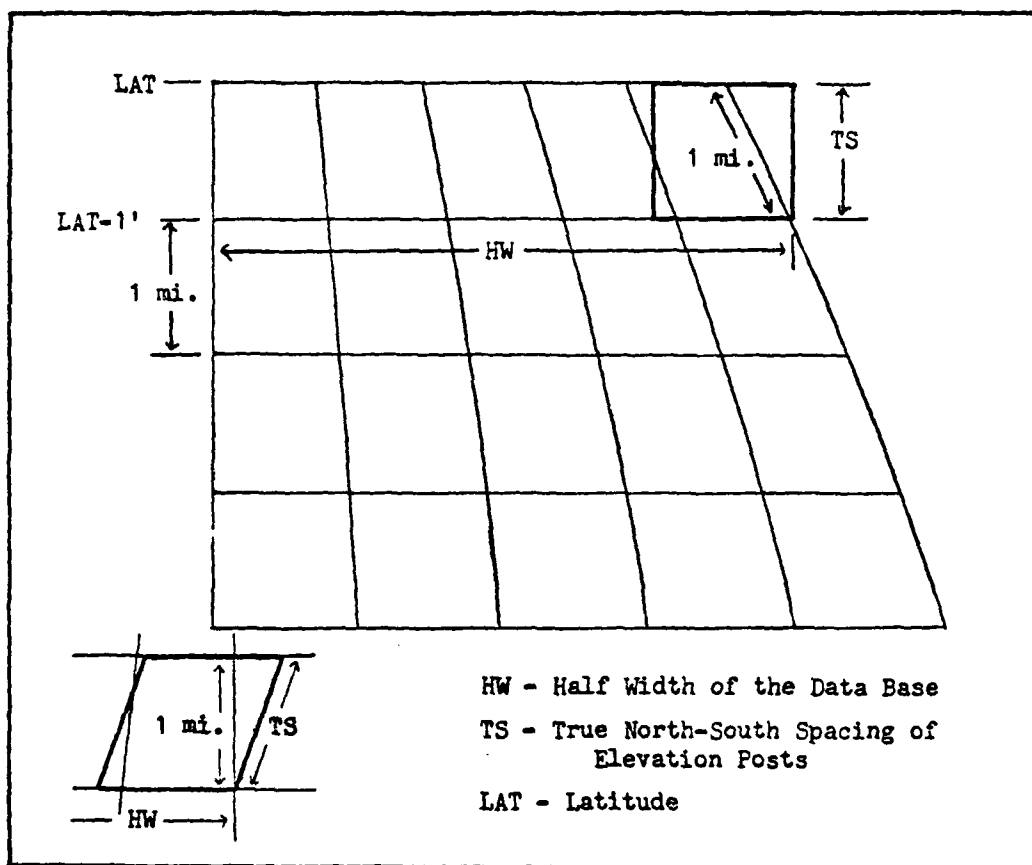
27

Figure 3-5: Grid Spacing Error
for a 1 Nautical Mile Grid
Exaggerated for Clarity

HW - Half Width of the Data Base

TS - True North-South Spacing of
Elevation Posts

LAT - Latitude

Let

   dLat = the change in latitude between adjacent posts
   Lat = the maximum latitude in the data base
   gs = the grid spacing in meters
   HW = 1/2 the total East-West width of the data base.

Then

   dx := HW * (1 - (cosine(Lat) / cosine(Lat-dLat)))

   $TS := square\_root((gs)^2 + (dx)^2)$

   Error := ((TS-gs) / gs) * 100%

For a 500 nautical mile wide data base that extends up to 60°N and has a dLat = 3 seconds, gs = 92.66 meters, TS = 93.39 meters, and the maximum spacing error is 0.8%. The change in spacing is 0.73 meters and is negligible compared with the 130 meter positional accuracy objective for the DTED used as a source. Figure 3-6 is a plot of the maximum spacing error vs the total East-West width of a data base for several latitudes.

For these same reasons, the columns of the data base are not true North-South lines. Only the center column lies on a longitude line and is therefore true North-South, the remaining columns tend to turn away from the center (Figure 3-7). The deviation from true North increases as the the distance from the center column increases and as the distance from the equator increases. At a distance "dist" from the center column the deviation from true North, "dNorth", can be found by
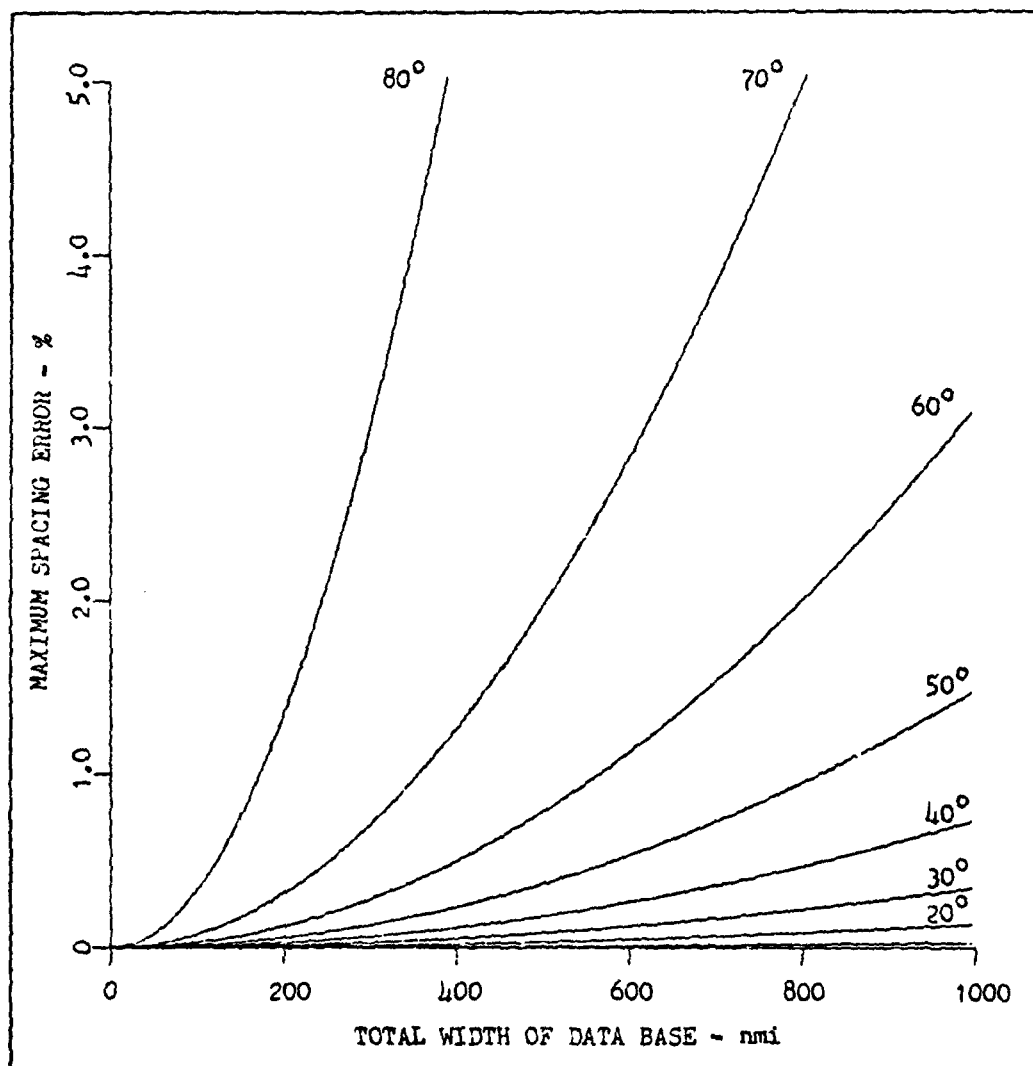
29

Figure 3-6: Maximum Spacing Error vs Total Width of Data Base

dx := dist * (1 - (cosine(Lat) / cosine(Lat - dLat)))

dNorth := arctangent(dx / gs)

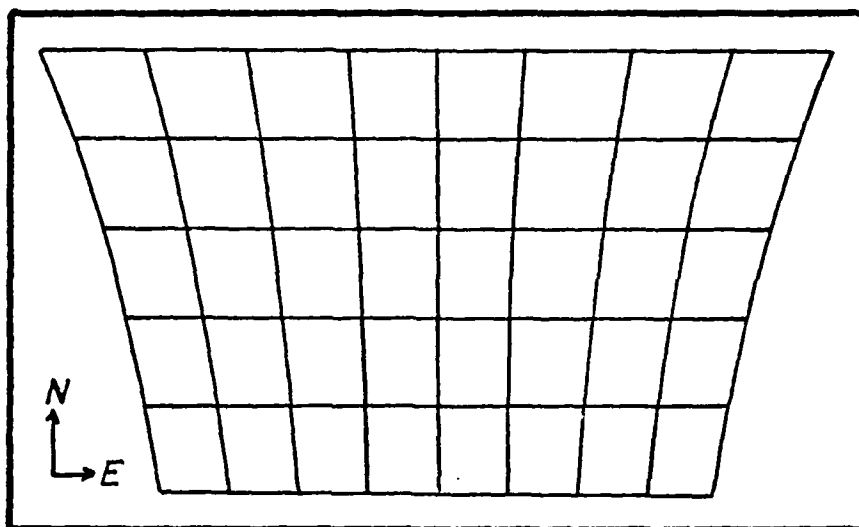For the same 500 nautical mile wide data base, the

30

Figure 3-7: Rows and Columns of the Data Base Drawn on a
True North-South, East-West Grid
Exaggerated for Clarity

maximum deviation is 7.18° and occurs at 250 nmi from center
and at 60°N latitude. Figure 3-8 is a plot of the column
deviation from true North vs distance from the center column
for several latitudes.

Since the data was compacted into 9 bit offsets, the
maximum elevation difference between adjacent posts is
limited to plus or minus 255 meters (837 feet). With a
92.6625 meter (304 feet) horizontal spacing between posts
this limit corresponds to a 70° slope. Because no elevation
post in either the DTED or the prototype data base can have
two elevation values, sheer cliffs are not allowed.
Therefore, the 9 bits offsets should not introduce any
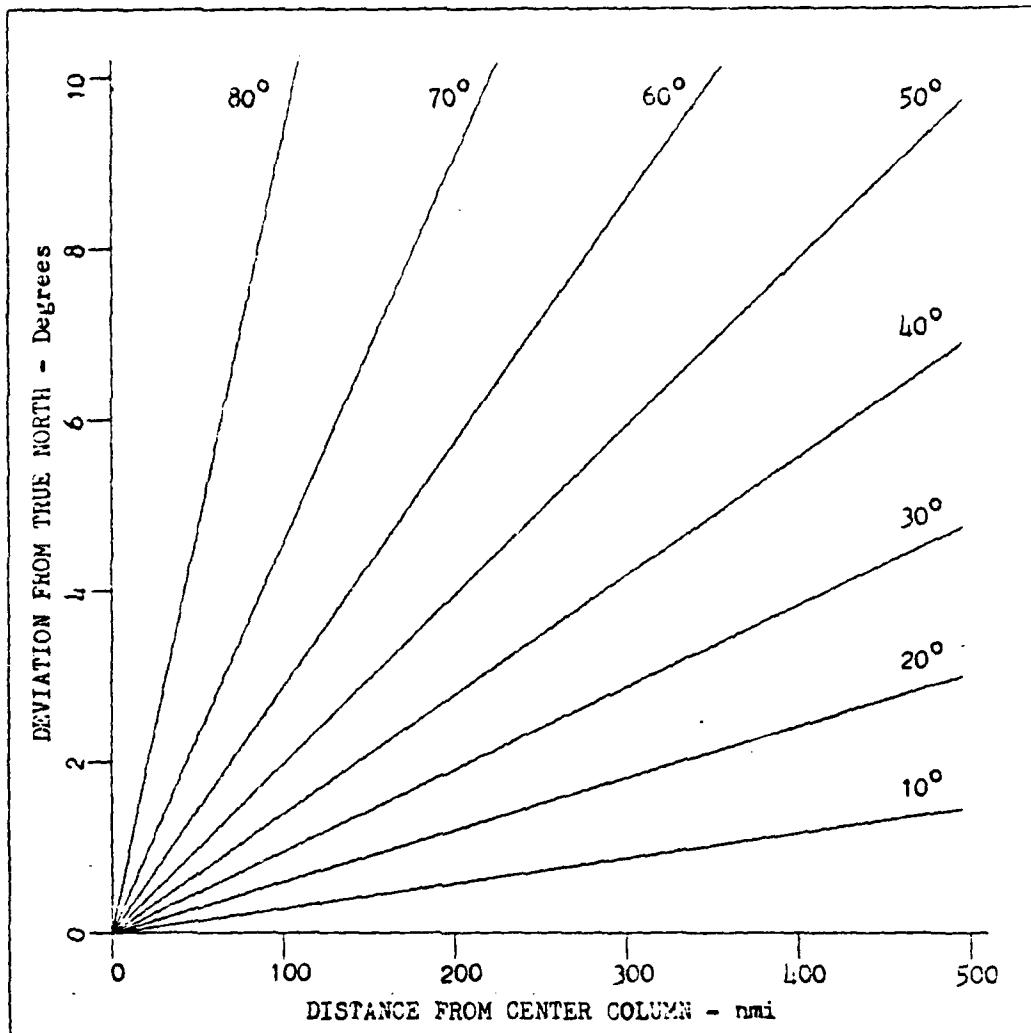additional errors. If the elevation difference between

31

Figure 3-8: Column Deviation from True North
vs Distance from the Center Column

adjacent posts exceeds 255 meters, the error will not be propagated to following posts during un-compaction. The compaction algorithm used would have computed the following offsets from the limited value.
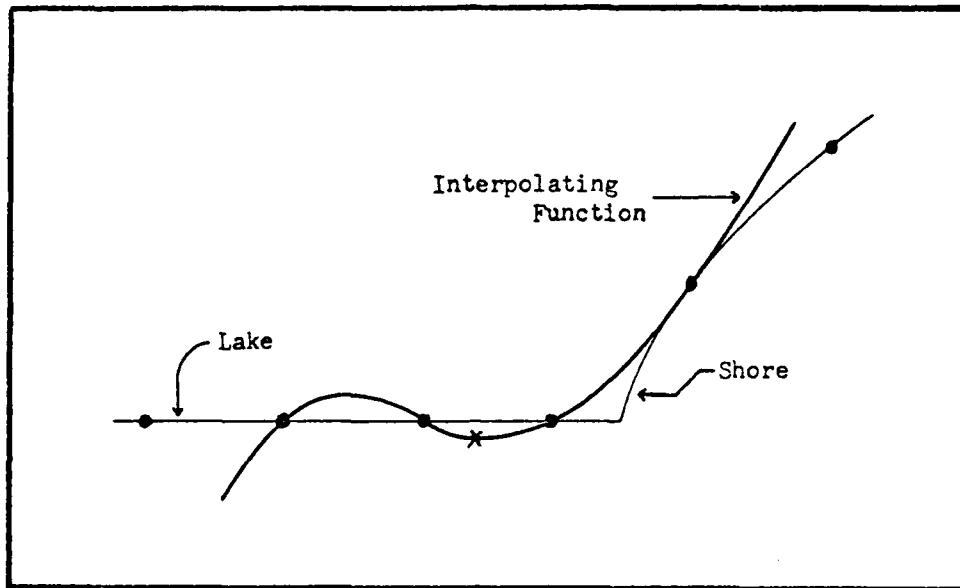
32

Figure 3-9: Interpolation Near a Steep Shore Line

The interpolation function used to regrid the DTED to the new data base coordinate system is a third order polynomial. This function works well over smoothly varing terrain, but has problems where the terrain has an abrupt change in slope. This is most noticeable where a body of water has a steep shore line. A value interpolated between the last post in the water and the first post on the shore tends to be below the water's surface (Figure 3-9). If the area to be regridded is on a sea coast and it is known not to contain any elevations below sea level, some errors could be easily corrected by not allowing negative elevations in the new data base. More sophisticated techniques would be needed to correct errors around lakes at higher elevations.

33

4. TESTING AND RESULTS

4.1 Construction

A data base was constructed from 70 files (14 magnetic tapes) of Level 1 DTED. The source files covered the area 42°N to 49°N latitude and 125°W to 115°W longitude. See Figure 4-1. The DTED files contain over 100 million elevation values and describe 176,520 square nautical miles of terrain in the North-Western Unites States. The constructed data base covers a slightly smaller area because the DTED does not cover a rectangular area. The new data base contains 65.52 million elevation values over a 163,800 square nautical mile area. See Figure 4-2. The data base has the following defining parameters:

```
Base latitude = 42° 00' 00" N
Center longitude = 121° 00' 00" W
Half width = 195 nautical miles
Height = 420 nautical miles
Grid spacing = 92.6625 meters
```

The four corners of the data base are located at

```
NW  -  48° 59' 57" N,   124° 57' 14" W
NE  -  48° 59' 57" N,   115° 02' 46" W
SW  -  42° 00' 00" N,   124° 22' 24" W
SE  -  42° 00' 00" N,   115° 37' 36" W
```
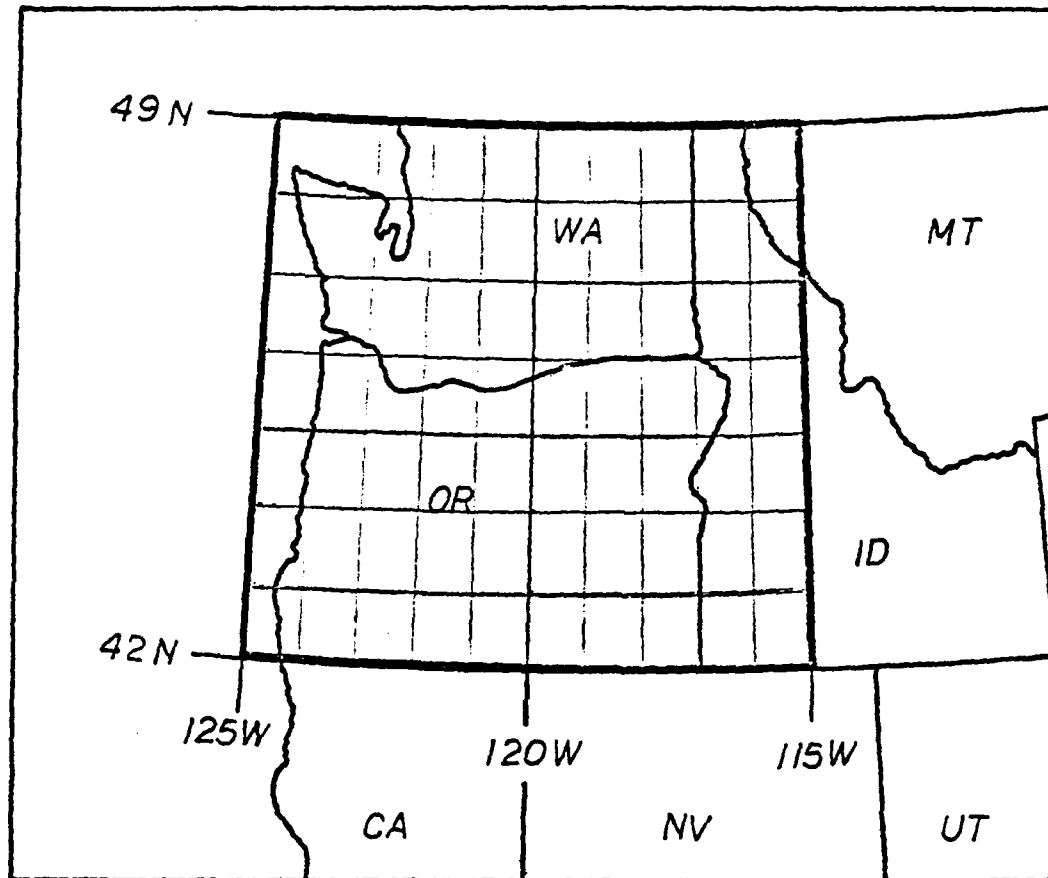
Figure 4-1: Area Covered by the DTED Files
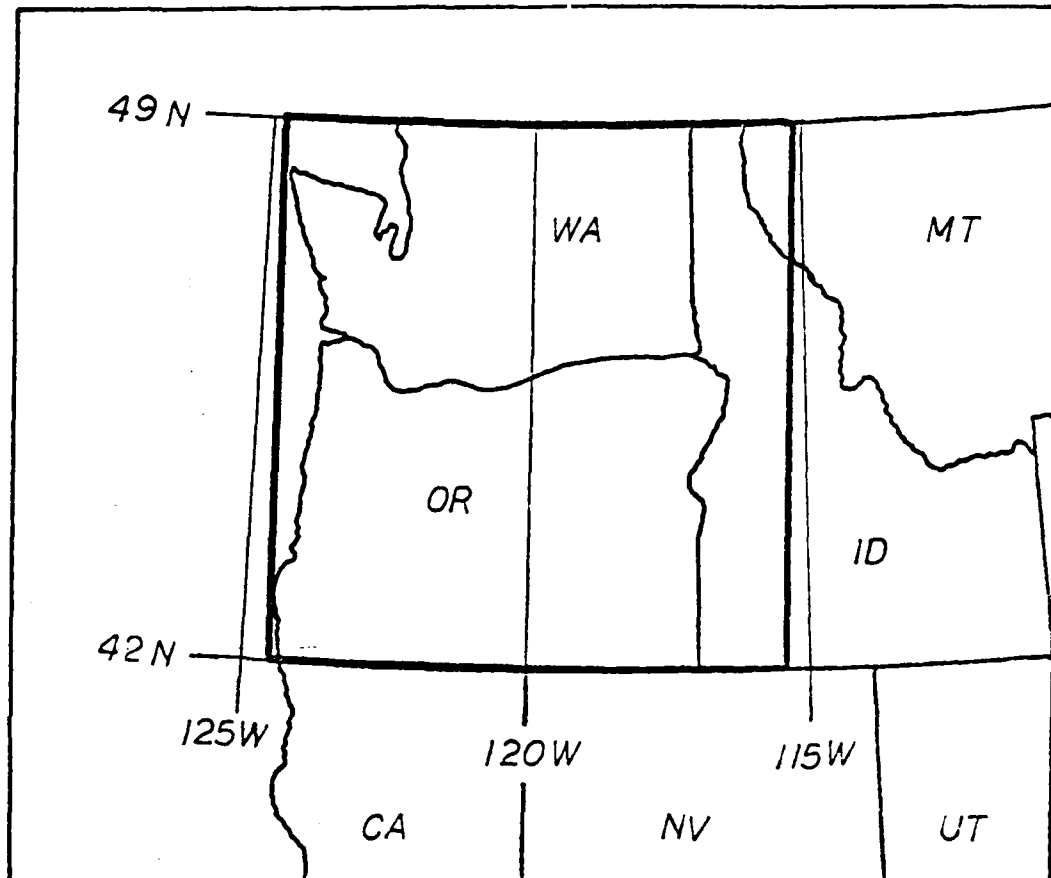
Figure 4-2: Area Covered by the Prototype Data Base

Because of the enormous amount of data the construction process was divided into several steps and the data base assembled in parts. The DTED was divided into seven one degree latitude bands. Each band contains 10 files and covers the area between two integer degree latitudes (e.g. 42°N to 43°N). All 10 files in a band were transfered from tape to disk. The data regrided from each band was placed

36

into 120 files, each containing 195 records. Each regridded file covered a one nmi by 195 nmi area either East of West of the center longitude. This was done for three reasons. If the system were to fail or if execution were interupted for any reason, the regridding program could be restarted anywhere in the band with little work lost. These files could be transfered to magnetic tape to free-up disk space. And because these files contained the elevation data in an un-compacted form, all or part of the data base could be transferred to another computer more easily.

When the band was completely regridded and all 120 files were written on magnetic tape, the 10 source DTED files were deleted from the disk. The process was repeated for the next latitude band. The final step was to take the 840 regridded files, compact the data and place it into a single file.

The latitude bands do not need to be regridded in order, but the 840 files must be added to the data base file in proper order. The process begins with the southern most pair of files, first the file West of center, then East. They are followed by the next pair to the North, and then all remaining files. The compaction and appending to the end of the data base could be interrupted at any time and restarted at the beginning of the file currently being added.

The operation to regrid the DTED required about 0.91

37

seconds of CPU time and 2.09 seconds of elapsed time per square nautical mile. To regrid the entire area required about 41 hours of CPU time and 95 hours of elapsed time. The program to compact the data ran much more quickly, requiring 0.21 seconds CPU and 0.39 seconds elapsed time per square nautical mile.

A total of 51 CPU hours and 113 elapsed hours were required to construct the data base. This does not include any time spent reading and writing files to magnetic tape. Adding these times would up the total to around 60 and 140 hours respectively. Since these program were usually run at night when the system was not heavily used, the run times were not an important consideration. The program code was written for simplicity rather than efficiency, and therefore the run times could be improved. This is especially true of the regridding program, since it often read the same data from the disk twice.

The regridding program also checked for interpolated values below sea level. Since the area covered by the data base does not have any negative elevations, these were obvious errors, and were changed to 0 (sea level). Of the 8400 elevations posts along the Pacific coast and thousands more along coastal inlets, only several hundred dips below sea level were found. Almost all of these were only one

38

meter below. Less than fifty dipped to two meters, and only a few to three meters. None went more than three meters below sea level.

The program to compact the data tagged all records that had an elevation difference between adjacent post greater than the allowed 255 meters. It also looked for differences larger than what would fit into 8 bits (127 meters). No indication of the 9 bits being a limiting factor were found. However, there were about a thousand places in which an 8 bit limit would have introduced an error.

4.2 Accuracy

The fidelity of the prototype data base was checked by trying to reproduce the source DTED. The same interpolating scheme was used to regrid the prototype data base to DTED coordinates. The results were dependent upon the terrain. Over smooth, flat area, 100% of the original DTED posts could be recovered exactly. Over mildly rugged terrain (e.g. rolling hills), 83% were recovered exactly. The remaining 17% of the posts differed from the DTED by an average of 1.3 meters, and the maximum error was 5 meters. Since all elevations are specified by integer values the minimum error was 1 meter. When averaged over all posts in the area the error was 0.225 meters per post. The worst case was over very rugged terrain. Only 46% of the posts could be

39

recovered exactly. The average error for the remaining 54%
was 1.91 meters, and the maximum error was 13 meters. When
spread over all the posts in the area the average error was
1.03 meters per post.

4.3 Access Time

All testing was done under the "TOPS-10" Operating
System in the normal time-sharing environment. However, all
the run-time tests were performed late at night, when no one
else was using the system. The tests were also run from a
high priority run-time queue. The "DECsystem-10" Pascal
functions TIME and RUNTIME were used to test the elapsed and
CPU times of procedures using the data base. To compensate
for the time the testing functions require, average execution
times were subtracted.

4.3.1 Retrieval

The average elapsed time required to fetch a record from
the disk was found to be 18 milliseconds using the random
access procedure "Setpos", and 9 milliseconds using the
sequential access procedure "Get". The difference between
the two times is due primarily to the fact that the "TOPS-10"
monitor sets up a buffer ring and reads ahead in the file.
This monitor function was used by reading the file sequential
where ever possible. In this manner the average elapsed time
required to read a record on disk was reduced to about 11
milliseconds.

40

4.3.2 Unpacking

Once the record is in the file buffer, it must still be un-compacted before it is used. This was found to require substantially more time than reading the record - approximately 34 milliseconds.

The exact implementation of the unpacking was left up to the non-optimizing Pascal compiler. If necessary this time may be reduced by writing a more efficient assembly language routine.

The overall time required to read and unpack a record was found to average approximately 46 milliseconds.

4.3.3 Interpolation

To obtain a elevation from the data base using the interpolating procedure "New_post" (see section 3.4.2), requires about 0.88 milliseconds of elapsed time. However, it required approximately 2.5 seconds to interpolate 2500 values from an array already in core memory.

Figures 4-3 through 4-6 are pictorial displays of elevation data interpolated from the data base. Each figure contains 2500 elevation values covering a square area. All values were obtained using "New_post". Table 4-3 lists the time required to prepare the display lists for each of the figures, starting with reading the records from disk and ending with the displayed list prepared in core memory.

LINEAR INTERPOLATION				
NUMBER OF POSTS	GRID SPACING METERS	AREA SQ NMI	NUMBER OF RECORDS READ FROM DISK	AVERAGE ELAPSED TIME SECONDS
2500	50	1.75	9	3.13
2500	100	6.99	25	3.77
2500	200	27.96	49	5.04
2500	500	174.8	225	12.8

Table 4-3: Required Time to Prepare a Display List
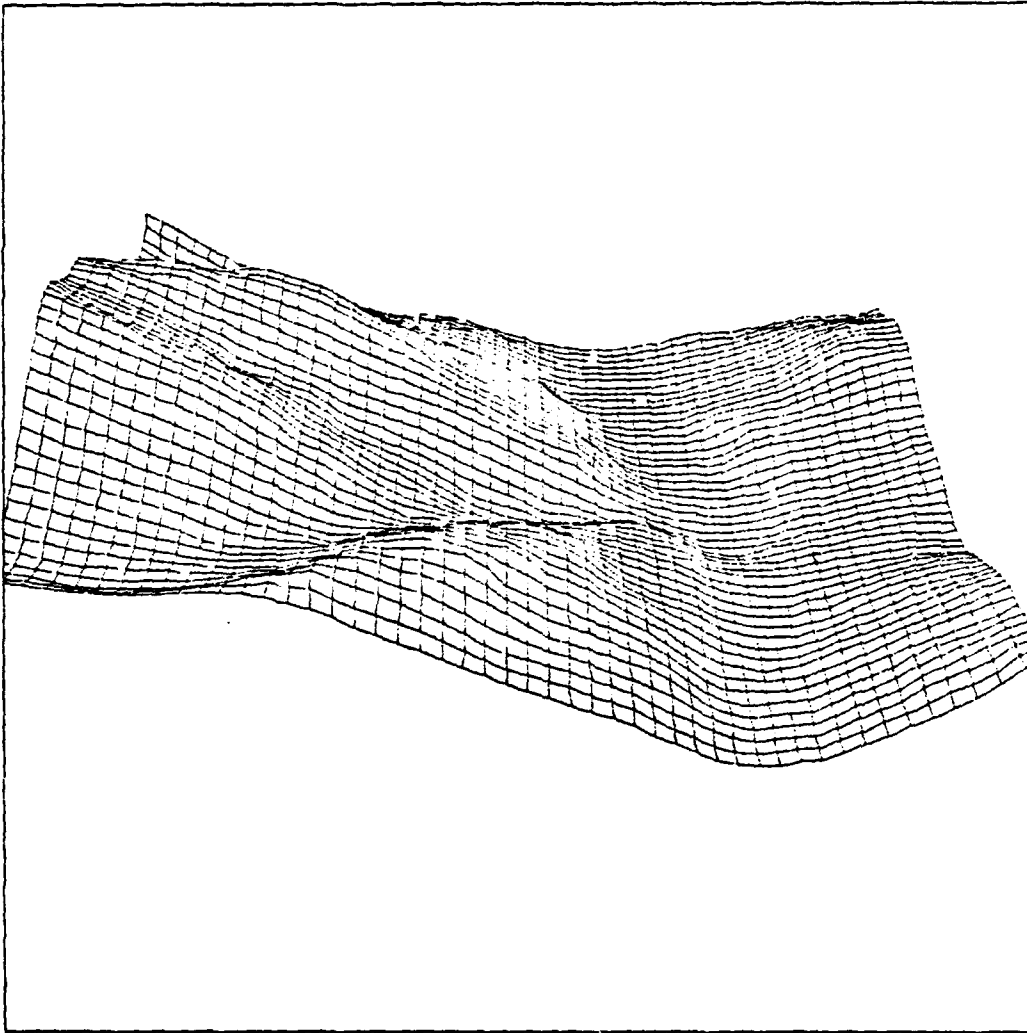
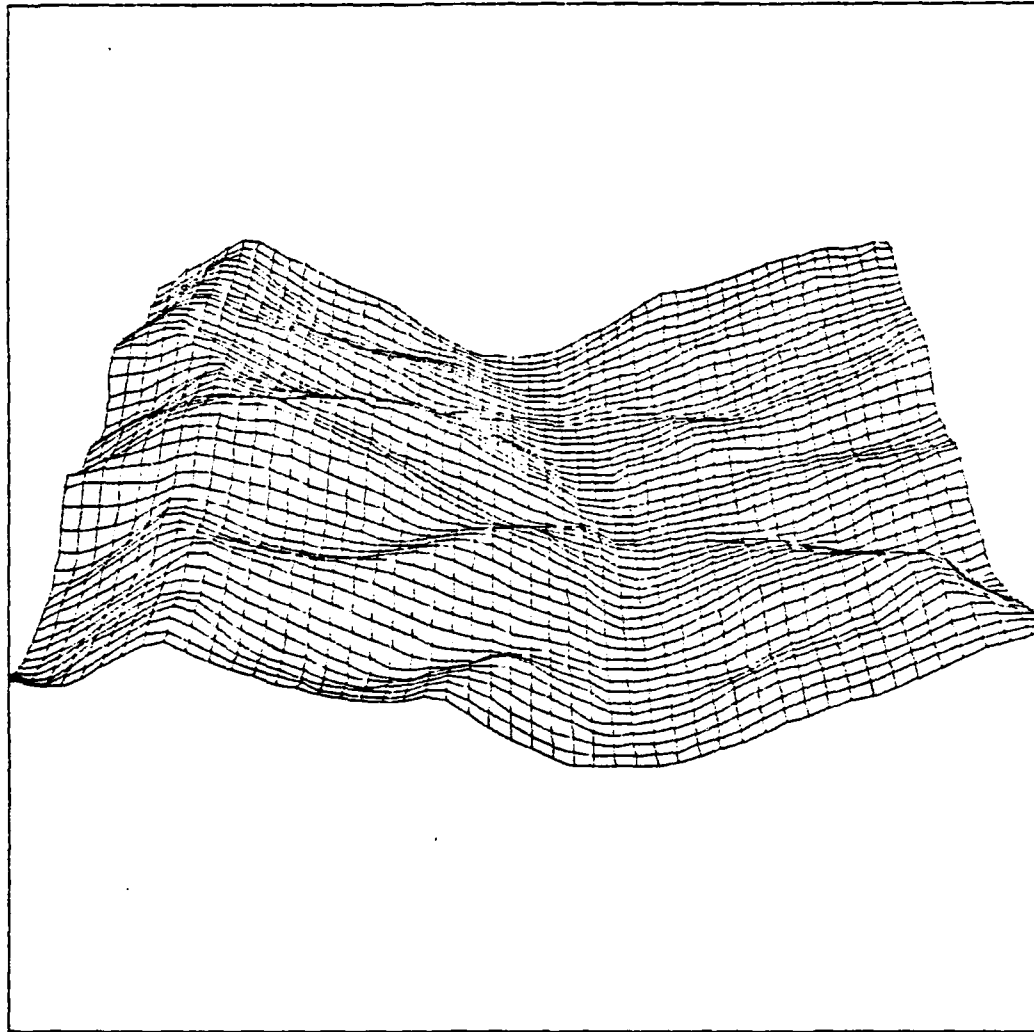Point of Observation = 6,000 Meters from Center

Area = 1.75 Square Nautical Miles

Grid Spacing = 50 Meters

Centered at
46° 20' 00" N, 121° 48' 00" W

Figure 4-3: Pictorial Display of Terrain
on a 50 Meter Grid
Linear Interpolation

43

Point of Observation = 12,000 Meters from Center

Area = 6.99 Square Nautical Miles

Grid Spacing = 100 Meters

Centered at
46° 20' 00" N, 121° 48' 00" W

Figure 4-4: Pictorial Display of Terrain
on a 100 Meter Grid
Linear Interpolation

Point of Observation = 24,000 Meters from Center

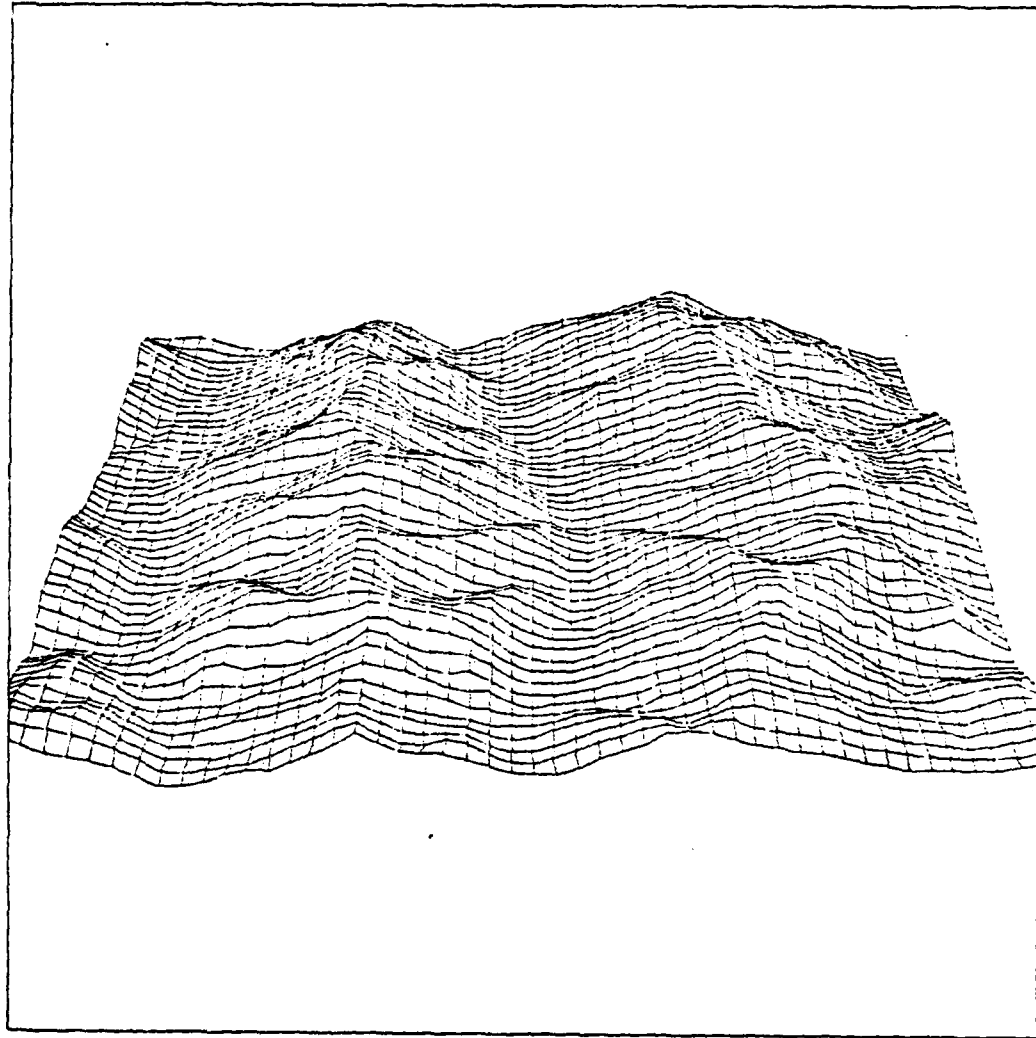Area = 27.96 Square Nautical Miles

Grid Spacing = 200 Meters

Centered at
46° 20' 00" N, 121° 48' 00" W

Figure 4-5: Pictorial Display of Terrain
on a 200 Meter Grid
Linear Interpolation

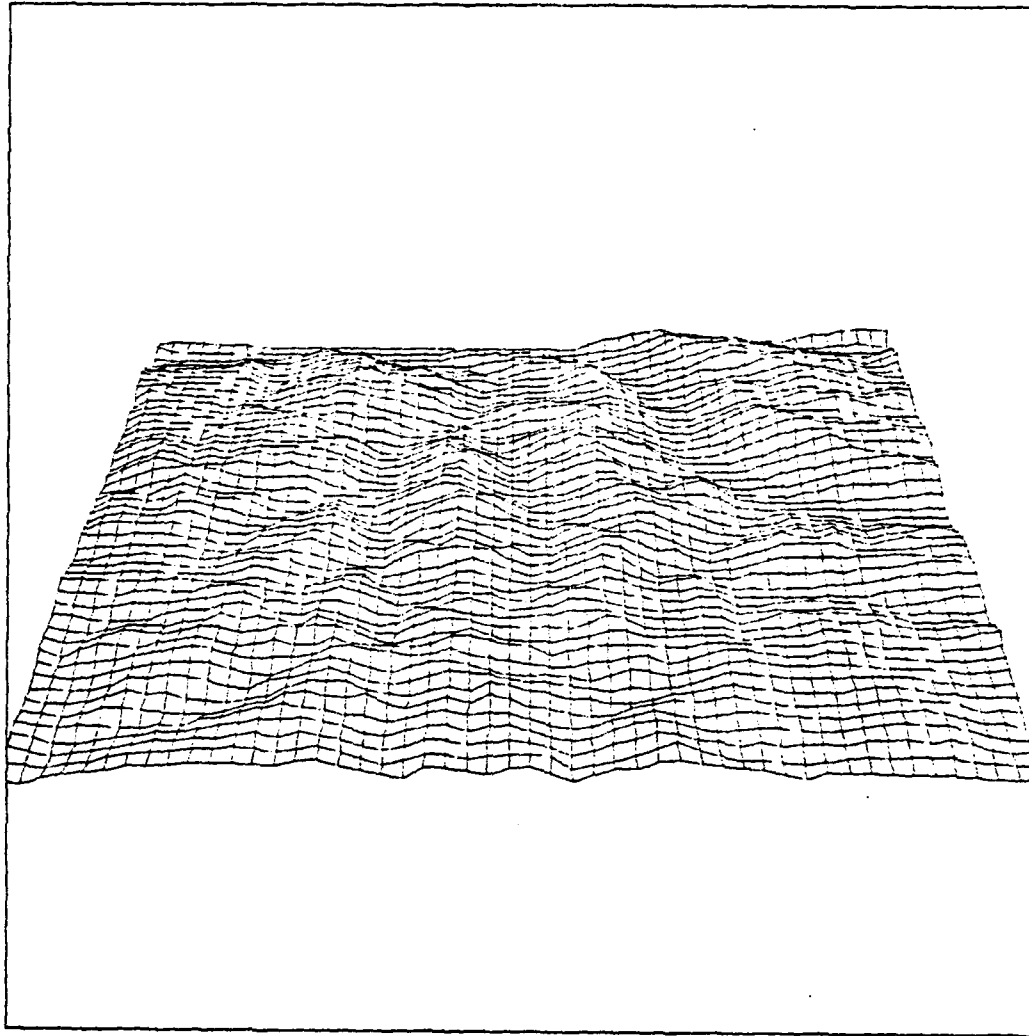45

Point of Observation = 60,000 Meters from Center

Area = 174.8 Square Nautical Miles

Grid Spacing = 500 Meters

Centered at
46° 20' 00" N,   121° 48' 00" W

Figure 4-6: Pictorial Display of Terrain
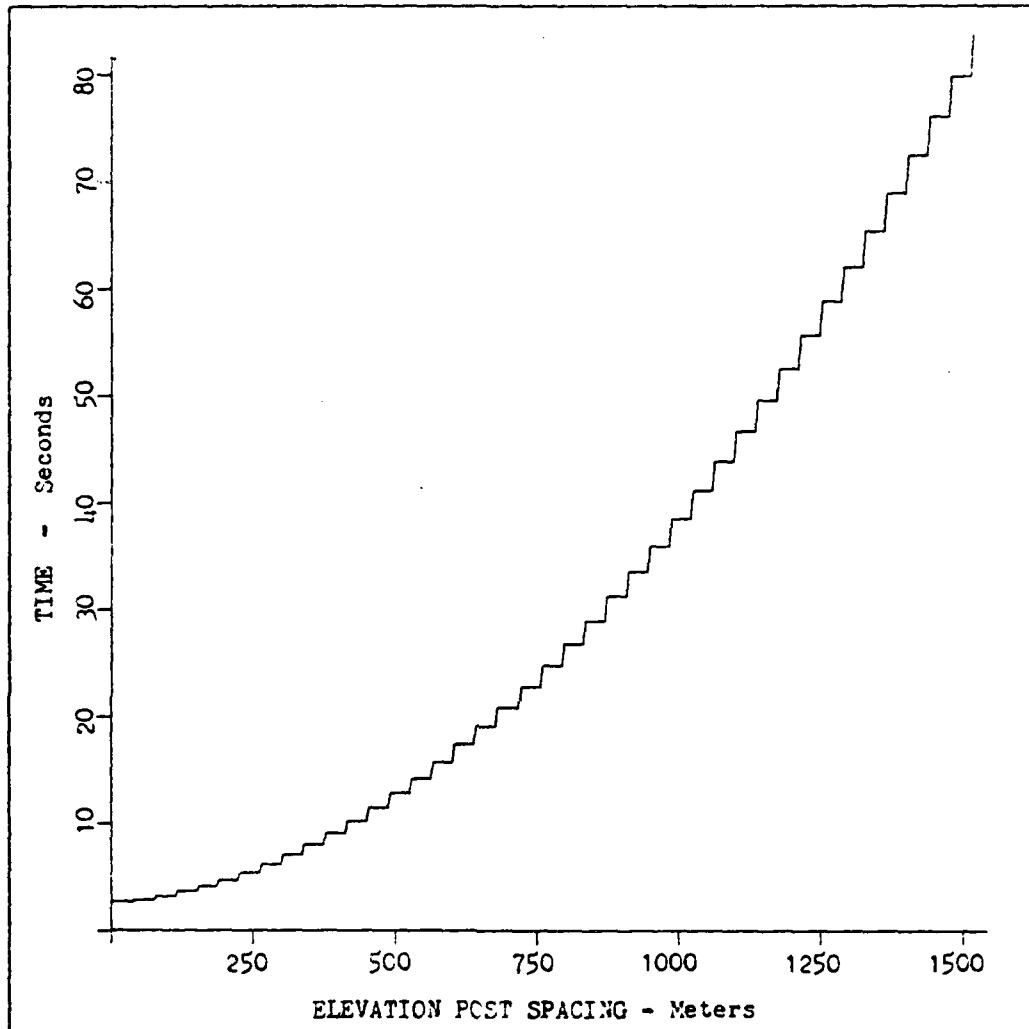on a 500 Meter Grid
Linear Interpolation

46

Figure 4-7: Plot of Time Required to Prepare a 2500 Node
Display List vs Node Spacing
Linear Interpolation

The time required to prepare a 2500 node display list can be estimated by allowing 46 milliseconds for each record read from disk plus 2.5 seconds for interpolation. Figure

47

4-7 is a plot of the elapsed time required to prepare a display list vs node spacing. The times shown assume that all 2500 values are found by linear interpolation, and that the worst case number of records was read from disk. For example, a display list on a 160 meter grid would cover a 4.23 by 4.23 nautical mile area. Therefore, a maximum of 36 (6 * 6) records would need to be read. The time required to prepare the display list would be 4.2 seconds, 1.7 seconds to read the records and 2.5 seconds to interpolate the elevation values. When producing multiple displays of adjacent and/or overlapping areas, this time can be improved because previously read records can be reused.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Construction

Although there is a slight loss in the fidelity of the
data, it is felt that the prototype data base is suitable for
any application in which the source DTED is suitable. The
loss of fidelity is due do the fewer data samples in the new
data base. Over the area covered by the prototype data base,
the DTED files averaged 572 elevation posts per square
nautical mile while the new data base has 400. But since the
sampling rate in the new data base matches the sampling rate
in the DTED in the North-South direction, the minimum
sampling rates for both are the same. For a data base
farther South, the difference in number of sample per sq nmi
will be less.

The longitudes of the posts in the new data base are not
readily available, but if in some application this is more
important than than the spacing between posts, the same
methods of compaction and organization can be used to
construct records which have an area of coverage defined by
lines of constant latitude and longitude, rather than a
distance from the center. It would not be necessary to
regrid to a new coordinate system. Therefore, there would be
no loss in fidelity, only an improvement in organization.

49

Although there is some distortion because the columns of the prototype data base do not follow true North-South lines, This distortion is only visual. All posts in the data base can be exactly located by its latitude and distance from the center column. The distortion is produced when displaying only the data on a constant interval grid. The spacing in the prototype data base varies from 92.66 meters at the center column to 93.39 meters at the far Northern corners. This is much less than the 60.76 to 68.86 meter change in the source DTED. The length of the center column of the new data base is 420 nmi, and the length of a side column is 420.7054 nmi. This is only a 1307 meter difference over the entire length, or a 0.17% error. This error is negligible when compared with the accuracy goal of the DTED.

It is believed that the interpolating function used to regrid the DTED to the new data base coordinate system is satisfactory for the vertical accuracy goal of the DTED (plus or minus 30 meters). Some improvement could be made by looking for the flat lake surfaces, and not allowing the interpolated values to drop below the surface before starting up the shore. Some improvement my also be found by using a two-dimensional function that models the surface, rather that the one-dimensional function along a line that was used.

5.2 Compaction

The time required to un-compact a record is significantly longer than the time required to transfer the record from disk to core memory. With efficient disk organization, the prototype data base will easily fit on a 200 MByte disk pack. Therefore, it is recommended that the data not be compacted if there is sufficient storage space. The time required to prepare a record for use can be reduced by 70%, if it does not need to be un-compacted.

If this method of compaction is to be used on a 32, 16, or 8 bit machine, it would be desirable to use 8 bits instead of the 9 used to store the offsets. It would be better to drop the low order bit of each value instead of the high order bit. If the high bit is dropped there will be several gross errors, but dropping the low bit will not be noticeable. About one half of the posts will be off by one meter, but this is negligible compared with the 30 meter accuracy goal of the DTED.

5.3 Disk Organization

The "DEC-10" file system fragments a file on disk and must look for a record before reading it. The read time could be improved by efficient disk organization. The data base records should have a physical relationship to the disk. That is, the rows and columns of the data base should

51

correspond to the tracks and sectors on the disk pack. The size and shape of the records can be varied to produce an optimum disk organization. The algorithms developed can be easily modified to work with any record size which covers a rectangular area.

5.4 Retrieval and Interpolation

The data base developed is capable of providing terrain data fast enough to simulate Mach 1 flight (660 knots). The display system that will be used in future tests of the data base has hardware translation and rotation of the display, making it is possible to simulate motion within a display list.

Figure 5-1 is a plot of the time required to produce a 2500 node display list vs node spacing, along with the time it would require an aircraft traveling a 660 knots to cover 1/4, 1/3, and 1/2 the distance across the displayed area. Somewhere around 1/3 this distance is probably the optimum distance to travel in the display before generating a new one. By the time an aircraft has covered 1/2 the displayed area, there would be little of the display left out front to see, and using 1/4 as the distance would leave little time for any other processing.

When flying at very low levels, only small areas are displayed, and few records read. Therefore, the bulk of the
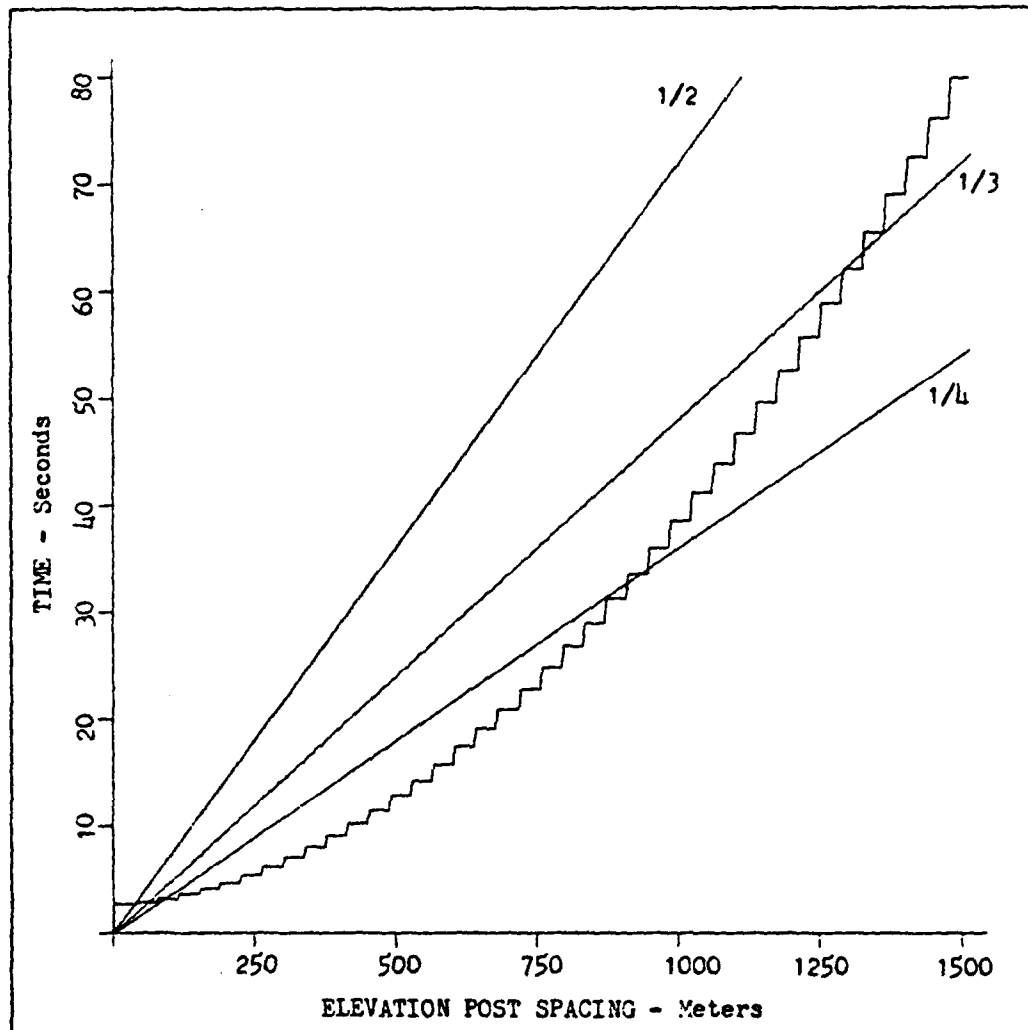
Figure 5-1: Plot of the Time Required to Prepare a 2500 Node
Display List vs Node Spacing – Linear Interpolation
and of Time Required by an Aircraft Traveling at
Mach 1 to Cover a Fraction of the Distance Across
the display

time spent preparing the display list is due to interpolation. For example, to to prepare a 2500 node display list over a 1.32 by 1.32 nautical mile area, requires 0.41 seconds to read and unpack the records and 2.5 seconds to linearly interpolate the values. The time required for interpolation can be significantly improved by just using the the elevation of the nearest post in the data base. This will reduce the interpolation time from 2.5 seconds to 0.83 seconds, but produces unacceptable results when displaying a grid smaller than the data base grid. Figure 5-2 is a perspective view of linear interpolated terrain on a 50 meter grid, and Figure 5-3 is the same view using the elevation of the nearest post in the data base.

Since Figure 5-2 covers such a small area, the edges of the display are visible even at this low level. For this reason and the time required to interpolate, it is recommended not to use a grid smaller than the data base grid. It is also recommended to use the values and locations in the data base rather than positions in between the data base posts. In this manner the interpolation or rounding time can be reduced to 0.61 seconds. Figure 5-4 contains the same view as Figures 5-2 and 5-3, but using the data base grid.

The data for Figure 5-4 was prepared in 1.35 seconds.
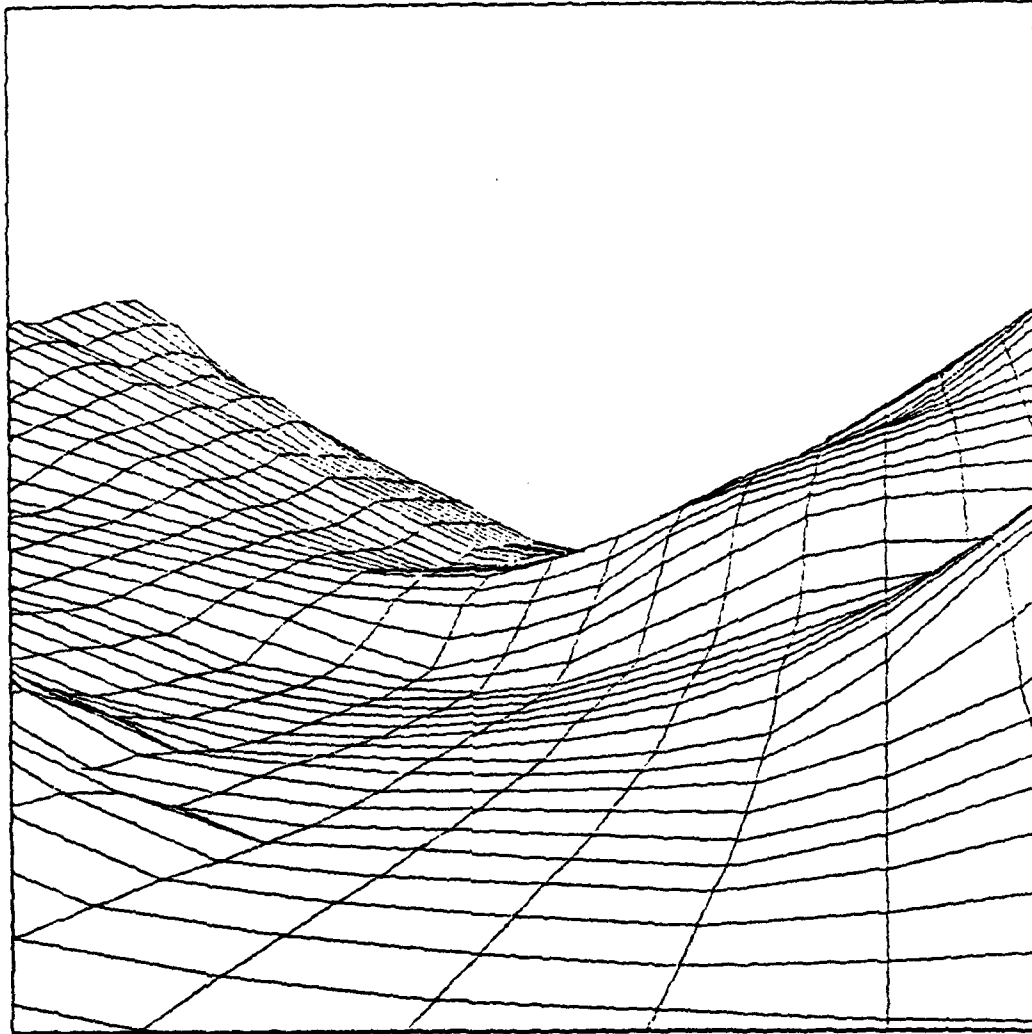
54

Position = 46° 20' 38" N,   121° 19' 45" W
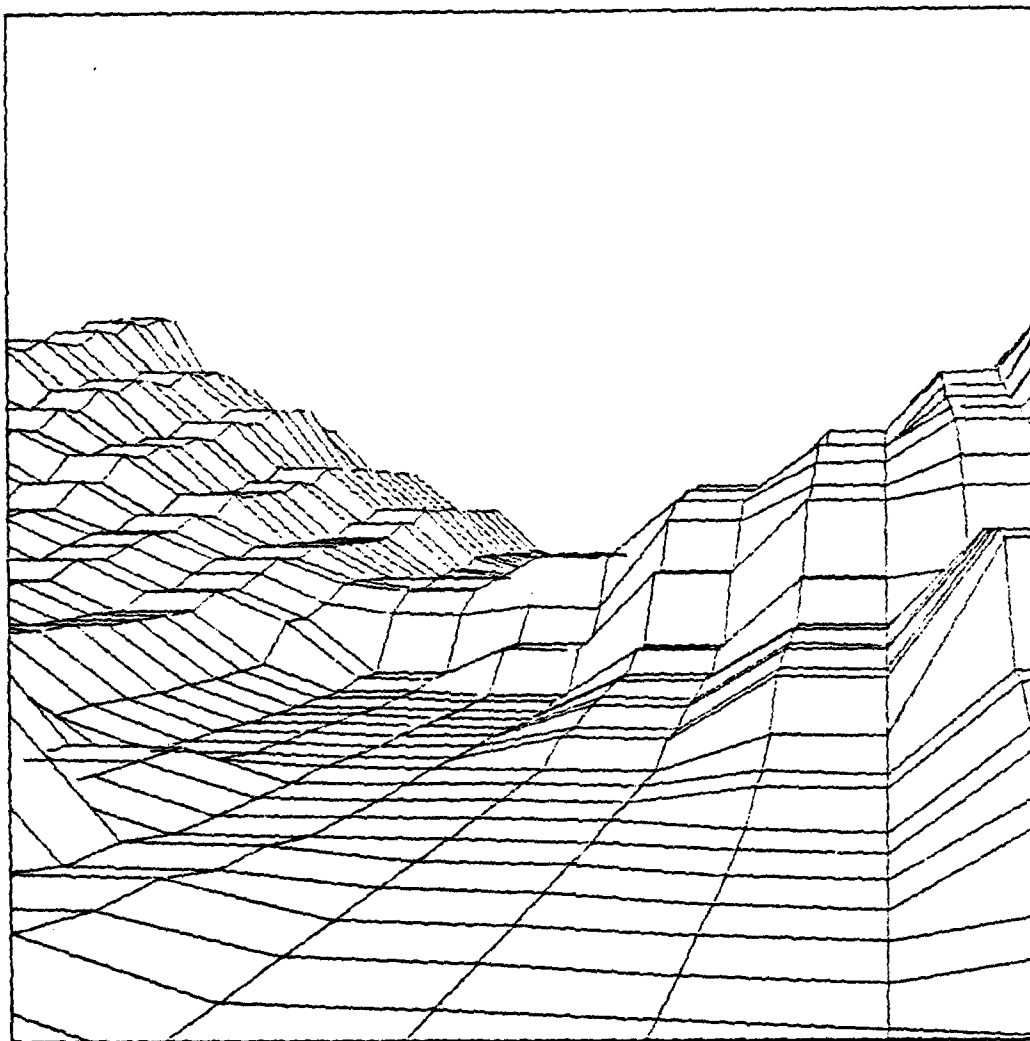
Heading = 170° (South-Southwest)

Altitude Above Ground Level = 110 Meters

Figure 5-2: Out the Window View of Terrain
on a 50 Meter Grid
Linear Interpolation

55

Position = 46° 20' 38" N, 121° 19' 45" W

Heading = 170° (South-Southwest)

Altitude Above Ground Level = 110 Meters

Figure 5-3: Out the Window View of Terrain
on a 50 Meter Grid
Rounded to Nearest Post
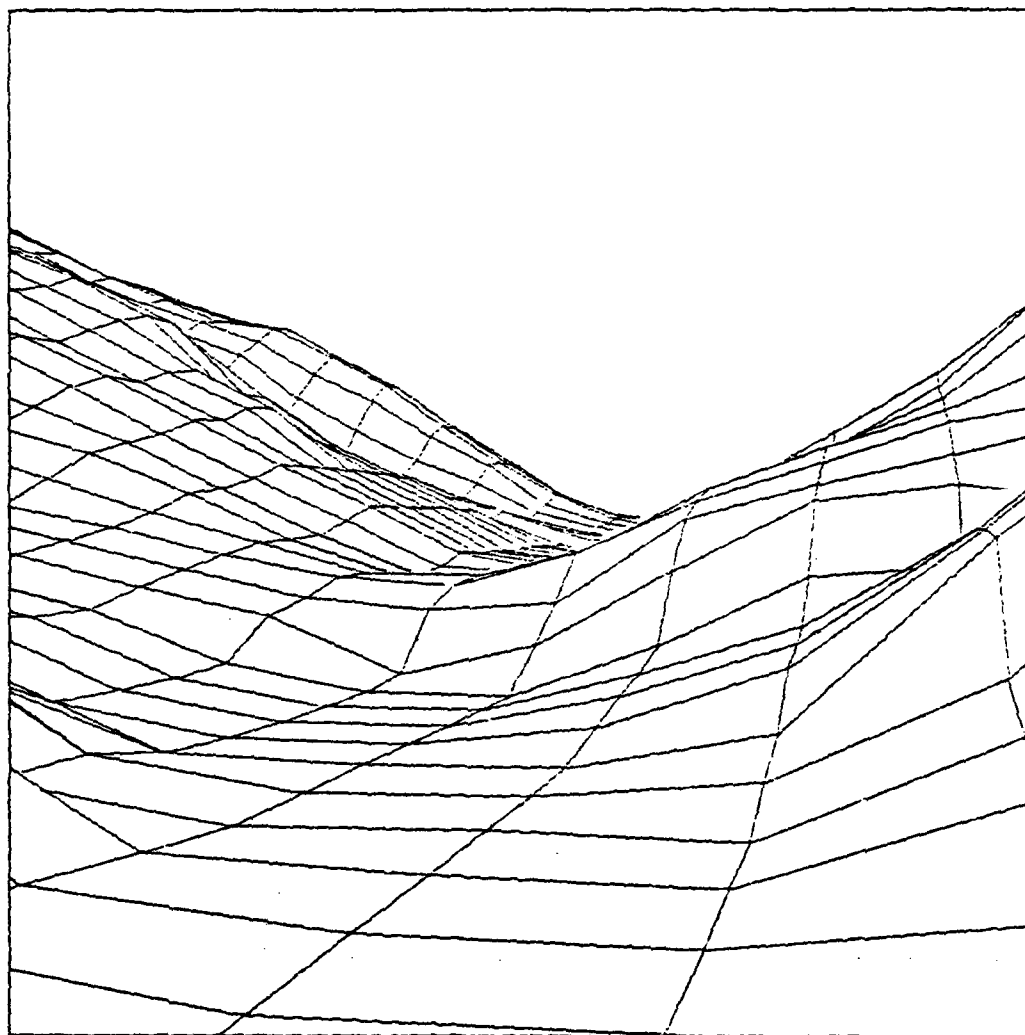
Position = 46° 20' 38" N,   121° 19' 45" W

Heading = 170° (South-Southwest)

Altitude Above Ground Level = 110 Meters

Figure 5-4: Out the Window View of Terrain
on a 92.6625 Meter Grid
Data Base Grid System

57

During that time an aircraft traveling at 660 knots would only travel 1/4 of a nautical mile or 460 meters. It would only pass over 5 out of 50 nodes across the display before the system could produce a new display list. Thus it is believed that this data base meets the requirements of a high speed, low level flight simulator. However, since the execution times for a hidden-line algorithm, and radar reflectance algorithms were not included, further research is required before an at night in weather simulator using digital terrain data is feasible.

BIBLIOGRAPHY

1. Breglia, Denis R. Survey of CIG Data Base Generation from Imagery. NAVTRAEQUIPCEN IH-318, Advanced Simulation Laboritory, September, 1980.

2. Drobot, Frank N. et al. Study of Digital Elevation Data Processing at DMAHTC. DMA 1-1, Battelle-Columbus Laboratories, March, 1979.

3. Hoog, T.; Dahlberg, R.; and Robinson, R. Project 1183: An Evaluation of Digital Radar Landmass Simulation. In Proceedings of NTEC/Industry Conference NAVTRAEQUIPCEN, IH-240, pp. 55-79. November 1977

4. Jablinske, R. J. Investigations in Polynomial Modeling and Gridded Arrays as Applied to Digital Terrain Models. ECAC-CR-80-017, IIT Research Institute, April, 1980.

5. Johnson, Lee W. and Riess, R. Dean. Numerical Analysis. Addison-Wesley Publishing Company, Reading, Massachuesetts, 1977.

6. Leberl, F. Interpolation in Square Grid DTM. ITC Journal, Vol. 5, pp. 756-800, 1973.

7. Mark, David M. Computer Analysis of Topography: A Comparision of Terrain Storage Methods. University of British Columbia, 1975.

8. . Produdct Specifications for Digital Landmass System Data Base. Defense Mapping Agency, July, 1977.

9. Schnitzer, Authur P. A Data Base Generation System for Digital Image Generation. Proceedings of 9th NETC/Industry Conference, November, 1976, pp. 103-113.

10. World Geodetic System Committee. The Department of Defense World Geodetic System 1972. The Department of Defense, May, 1974.

VITA

Harry D. Ross was born at Fort Meade, Maryland, on 28 May 1955. He enlisted in the Air Force in 1973. Upon completion of a Vietnamese Language Training program, in 1975, he flew aerial reconnaissance missions out of Kadena AFB, Okinawa. During 1976, he was selected for the Airman Scholarship and Commissioning Program. In 1980, he received the Bachelor of Electrical Engineering degree, from the Georgia Institute of Technology where he served as the AFROTC Cadet Corps Commander. Following graduation from AFIT, in December 1981, 2nd Lt. Ross will be assigned to the Avionics Laboratory at Wright-Patterson AFB, Ohio. He is a member of the IEEE, and currently president of the Delta Xi Chapter of Eta Kappa Nu.

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFIT/GEO/MA/81D-1	2. GOVT ACCESSION NO. ADA115 547	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* ANALYSIS AND PREPARATION OF A DIGITAL TERRAIN DATA BASE FOR FLIGHT SIMULATOR USE		5. TYPE OF REPORT & PERIOD COVERED MASTERS THESIS
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Harry D. Ross 2nd Lt USAF		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Institute of Technology (AFIT/EN) Wright-Patterson AFB, OH 45433		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Avionics Laboratory (AFWAL/AAAF-3) Wright-Patterson AFB, OH 45433		12. REPORT DATE December 1981
		13. NUMBER OF PAGES 67
14. MONITORING AGENCY NAME & ADDRESS(*if different from Controlling Office*)		15. SECURITY CLASS. *(of this report)* Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

1 5 APR 1982

18. SUPPLEMENTARY NOTES

Approved for public release; IAW AFR 190-17

F. C. Lynch, Major, USAF
Director of Information

Dean for Research and
Professional Development
Air Force Institute of Technology (ATC)
Wright-Patterson AFB, OH 45433

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Digital Terrain Data Base

Flight Simulator

Computer Generated Imagery

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The purpose of this thesis is to develop a digital terrain data base suitable for use in a high speed, low-level flight simulator. A 164,000 square nautical mile data base was constructed from data supplied by the Defense Mapping Agency. This paper discussed the construction and organization of the data base, as well as the data retrieval algorithms. It was demonstrated that the data could be accessed fast enough to simulate Mach 1 flight.

DD ₁ FORM JAN 73 1473   EDITION OF 1 NOV 68 IS OBSOLETE

END

DATE
FILMED

7 82

DTIC